Analysis of the Side-Effects on Latency Bounds of Combinations of Scheduling, Redundancy and Synchronization Mechanisms in Time-Sensitive Networks

Ph.D defense

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Public networks (e.g., the Internet)

Best-effort service

Time-Sensitive Networks

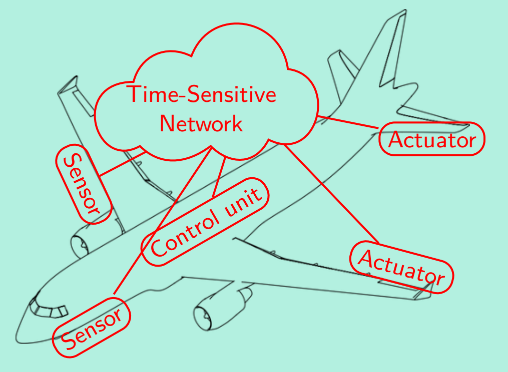
Deterministic Service

Bounded Latency

+ no loss by congestion

IEEE *Time-Sensitive Networking* (TSN)
IETF *Deterministic Networking* (DetNet)

Cyber-Physical Systems

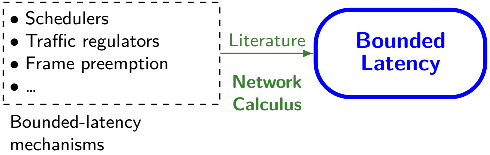


Safety-critical applications

Analysis of the Side-Effects on Latency Bounds of Combinations of Scheduling, Redundancy and Synchronization Mechanisms in Time-Sensitive Networks

Bounded Latency

Analysis of the Side-Effects on Latency Bounds of Combinations of Scheduling, Redundancy and Synchronization Mechanisms in Time-Sensitive Networks



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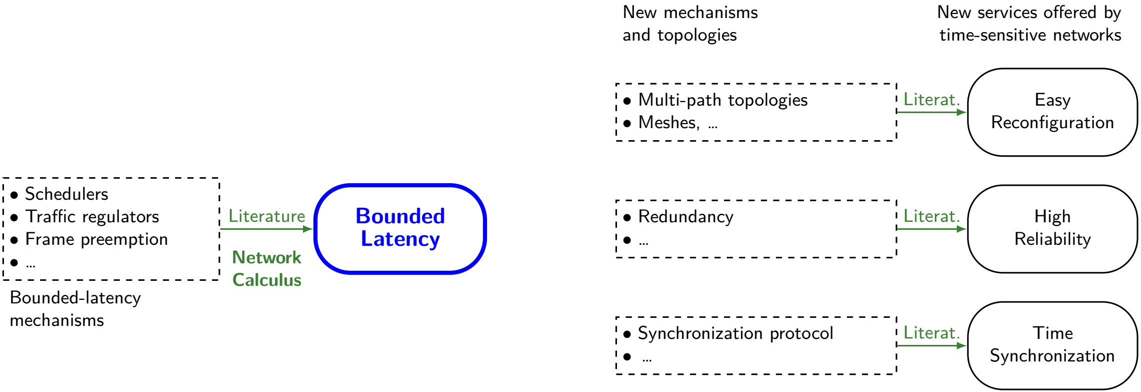

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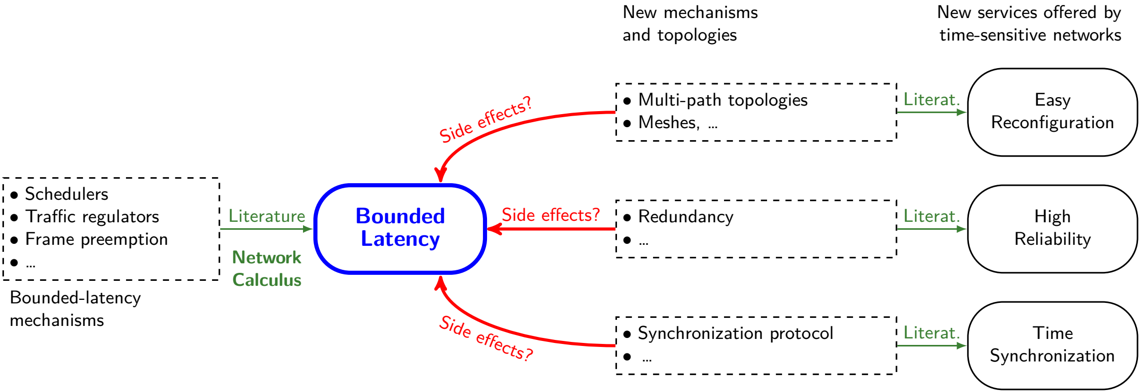

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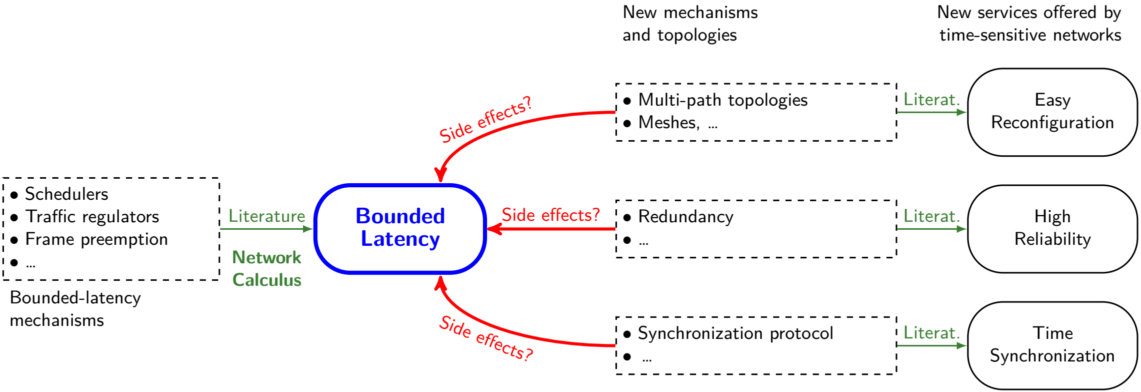
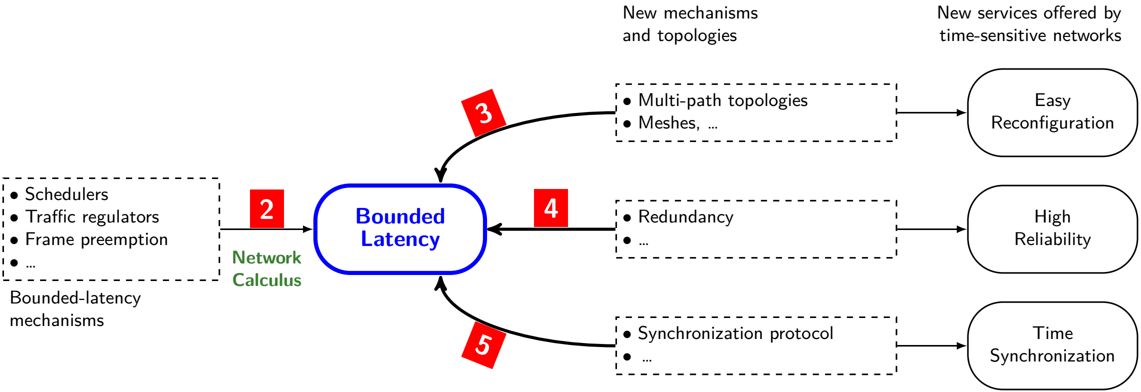
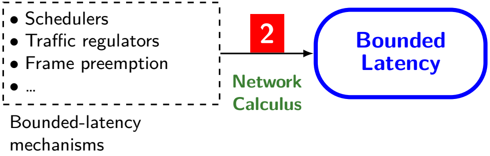


Outline of this Presentation



Network Calculus

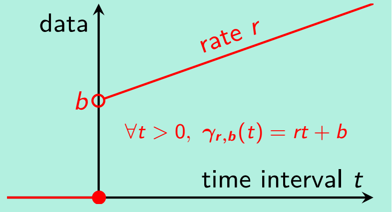


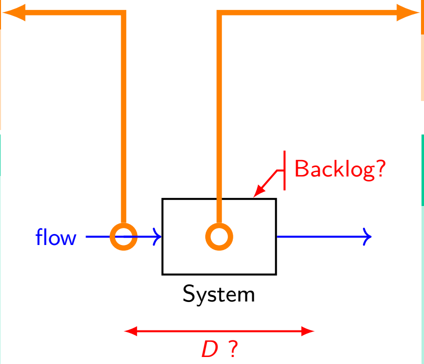
Network Calculus Relies on **Two Main Abstractions**

Arrival Curve α

upper-bounds the **maximum amount of traffic** of the flow over any interval

Leaky-Bucket $\gamma_{r,b}$



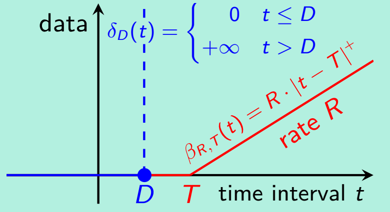


Guaranteed upper bounds?

Service Curve β

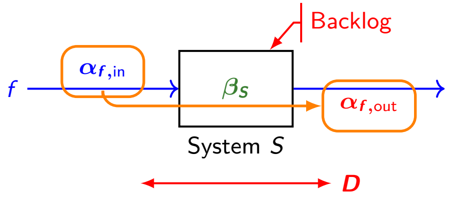
lower-bounds the **minimum amount of service** offered to the flow

Rate-Latency $\beta_{R,T}$
Bounded-Delay δ_D



$|\cdot|^+ = \max(0, \cdot)$

Network Calculus Provides **Upper Bounds** For Worst-Case Delay, Backlog and Output Traffic

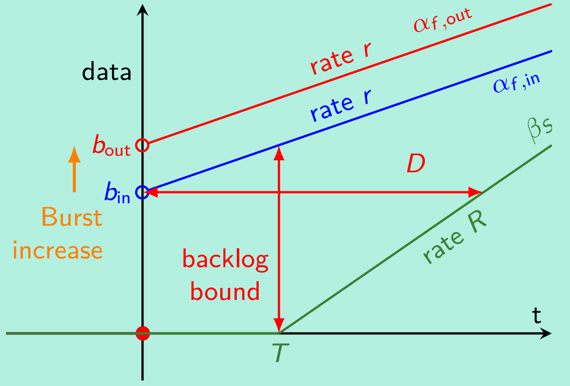


Network Calculus Main Result [Le Boudec, Thiran 2001]

Knowing $\alpha_{f,\text{in}}$ and β_S

- Backlog upper-bound
- Delay upper-bound
- Output arrival curve $\alpha_{f,\text{out}} = \alpha_{f,\text{in}} \oslash \beta_S$

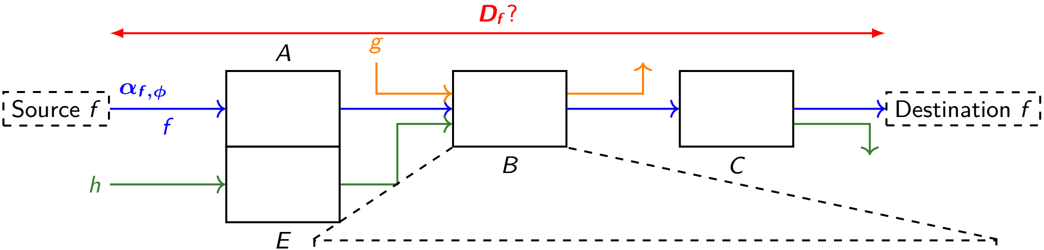
Leaky-bucket $\gamma_{r,b}$ and Rate-Latency $\beta_{R,T}$



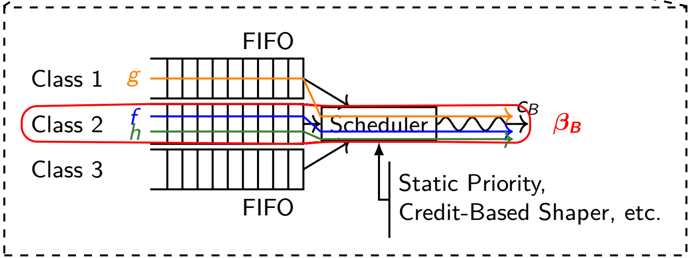
– [Le Boudec, Thiran 2001] Jean-Yves Le Boudec and Patrick Thiran [2001]. *Network Calculus: A Theory of Deterministic Queuing Systems for the Internet*. Berlin Heidelberg: Springer-Verlag. ISBN: 978-3-540-42184-9

$\oslash$: min-plus deconvolution. $(\mathfrak{f} \oslash \mathfrak{g}) : t \mapsto \sup_{u \geq 0}\{\mathfrak{f}(t+u) - \mathfrak{g}(u)\}$

From a Multiclass Network to n FIFO Networks

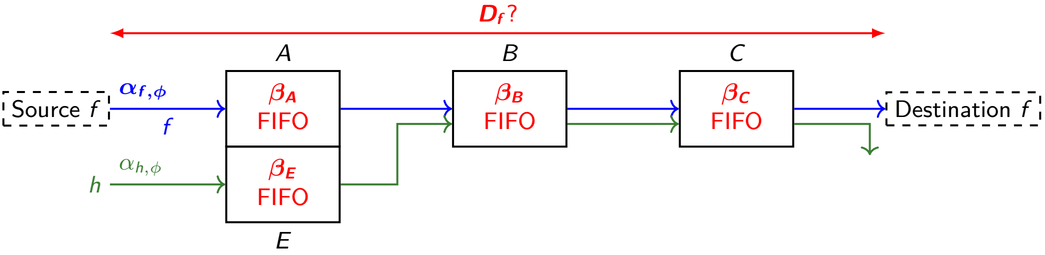


FIFO-per-class networks:



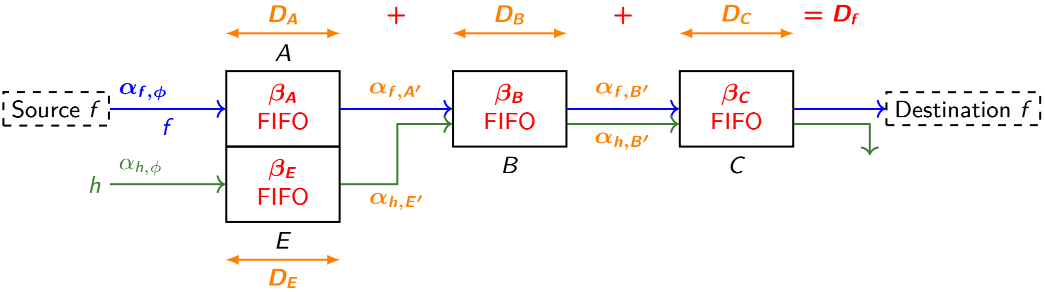
FIFO: First in, first out

From a Multiclass Network to n FIFO Classes: We Focus on **One Class**



Compositionnal approaches: compute end-to-end latency bounds in **FIFO** networks (active research field).

Total Flow Analysis, a Compositionnal Approach for Obtaining End-To-End Latency Bounds



Properties of TFA (Total Flow Analysis)

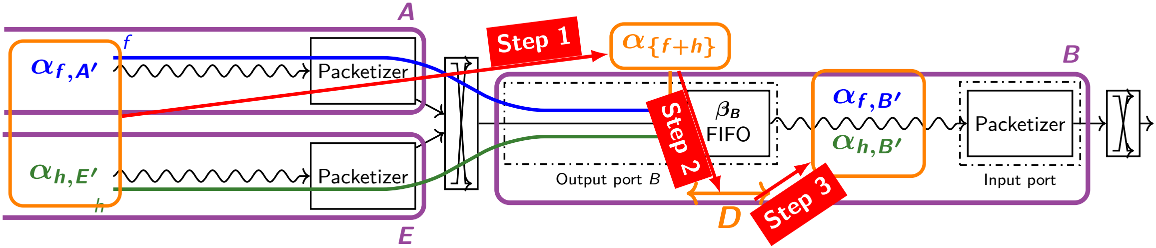
- **Optimal** worst-case upper bounds are **not guaranteed**.

but

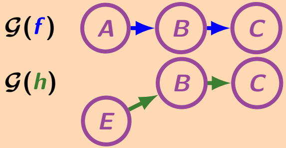
- **scalable** (linear complexity with the network's size) and **flexible** (new models are easy to integrate)

Total Flow Analysis Proceeds in Three Steps for each Node

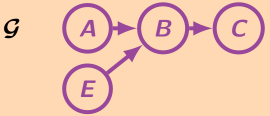
Zoom on B



Flow Graphs

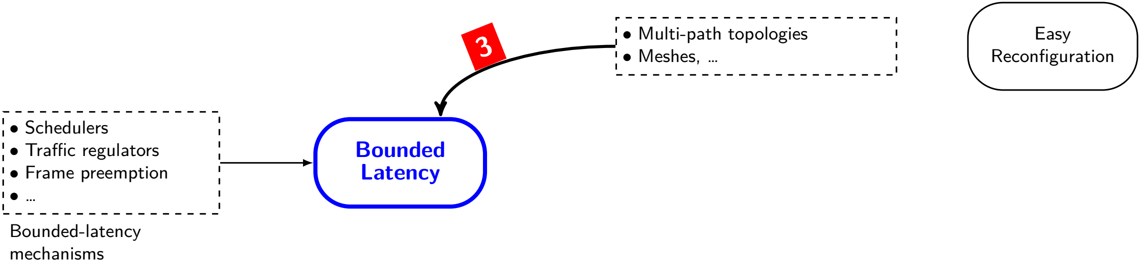


Graph Induced By Flows $\mathcal{G}$

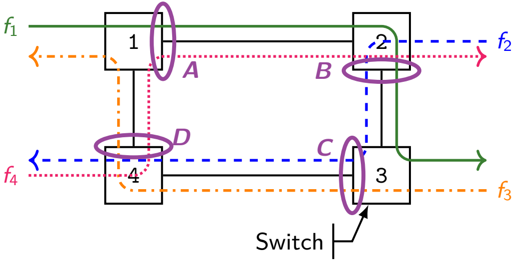


TFA is limited to networks with an **acyclic** graph $\mathcal{G}$: **feed-forward networks**.

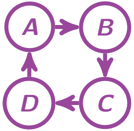
Multi-Path Topologies



A Possible Consequence of Using Multi-Path Topologies: **Cyclic Dependencies**



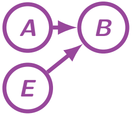
Graph induced by flows $\mathcal{G}$:



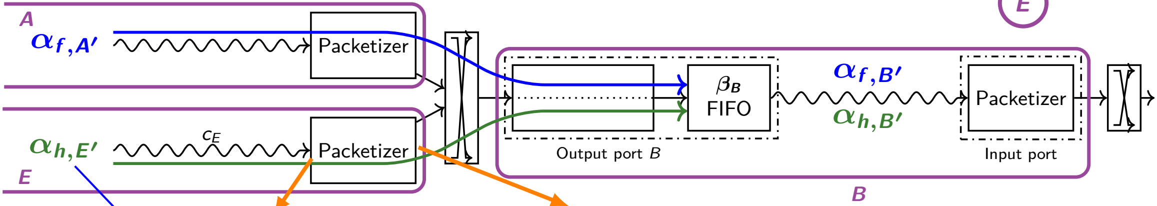
End-to-end latency bounds?

Fixed-Point Total Flow Analysis (FP-TFA)

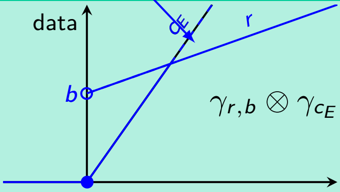
Fixed-Point Total Flow Analysis (FP-TFA): An **Improved TFA**



FP-TFA is based on Total Flow Analysis **with improvements**



Line shaping [Mifdaoui, Leydier 2017]



- Previous result: $+l_{max}$
- New result: $+l_{\max}\frac{r}{c_E}$

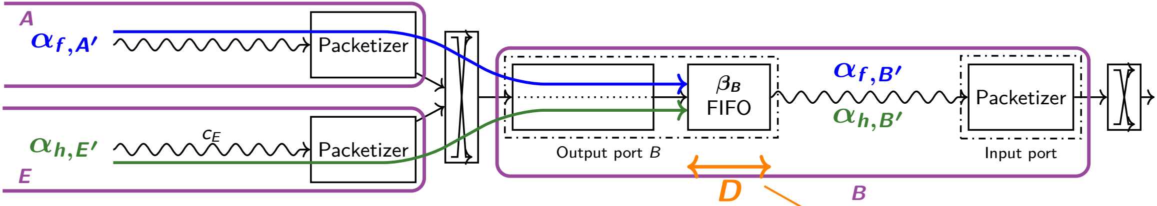
$\otimes$: min-plus convolution

$(\mathfrak{f} \otimes \mathfrak{g}) : t \mapsto \inf_{0 \leq s \leq t}\{\mathfrak{f}(t-s) + \mathfrak{g}(s)\}$

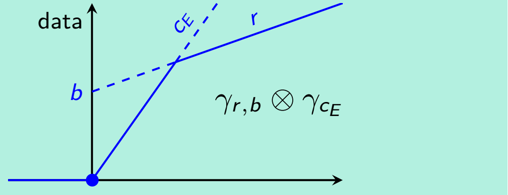
– [Mifdaoui, Leydier 2017] Ahlem Mifdaoui and Thierry Leydier [Dec. 2017]. "Beyond the Accuracy-Complexity Tradeoffs of Compositional Analyses Using Network Calculus for Complex Networks". In: *10th International Workshop on Compositional Theory and Technology for Real-Time Embedded Systems (Co-Located with RTSS 2017)*. Paris, France

Fixed-Point Total Flow Analysis (FP-TFA): An **Improved TFA**

FP-TFA is based on Total Flow Analysis **with improvements**



Line shaping [Mifdaoui, Leydier 2017]



- Previous result: $+l_{max}$
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[Mohammadpour, Stai, Le Boudec 2019]

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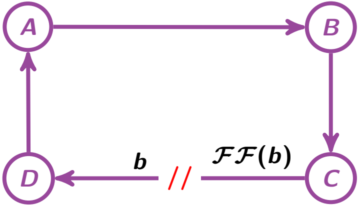
– [Mohammadpour, Stai, Le Boudec 2019] E. Mohammadpour, E. Stai, and J.-Y. Le Boudec [2019]. "Improved Delay Bound for a Service Curve Element with Known Transmission Rate". In: *IEEE Networking Letters*. DOI: 10.1109/LNET.2019.2927143

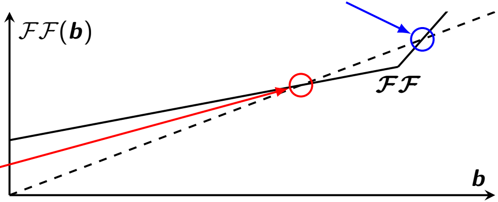
FP-TFA: A **New Fixed-Point Result** for Networks with Cyclic Dependencies

Leaky-bucket-constrained flows, **cuts** and **fixed-point**.



Before our result

[Bouillard, Boyer, Le Corronc 2018]



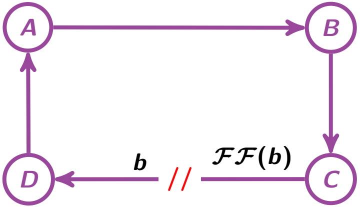
Theorem (Validity of the fixed-point)

If the network is **initialy empty**, and if $\overline{b}$ is non negative and such that $\mathcal{FF}(\overline{b}) = \overline{b}$, then the network is stable and $\overline{b}$ is a valid bound for the bursts at the cuts.

– [Bouillard, Boyer, Le Corronc 2018] Anne Bouillard, Marc Boyer, and Euriell Le Corronc [2018]. *Deterministic Network Calculus: From Theory to Practical Implementation*. Wiley. ISBN: 978-1-84821-852-9

FP-TFA: A **New Fixed-Point Result** for Networks with Cyclic Dependencies

Leaky-bucket-constrained flows, **cuts** and **fixed-point**.



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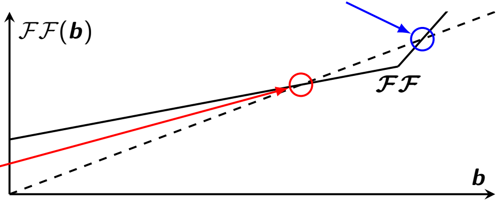
Before our result

[Bouillard, Boyer, Le Corronc 2018]



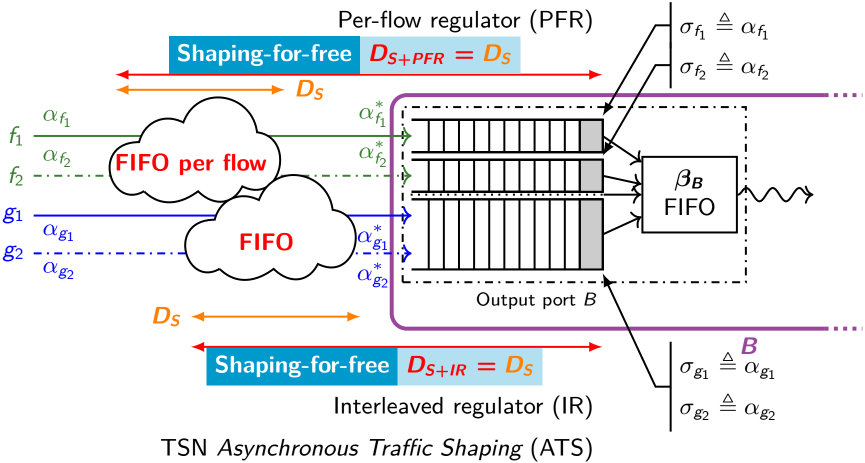
Sometimes, no fixed-point can be found!

[Andrews 2009]

There exist FIFO networks with cyclic dependencies and arbitrarily small load that are **unstable** (unbounded latencies).

– [Andrews 2009] Matthew Andrews [July 2009]. "Instability of FIFO in the Permanent Sessions Model at Arbitrarily Small Network Loads". In: *ACM Trans. Algorithms* 5.3. DOI: 10.1145/1541885.1541894

Traffic Regulators Break Cyclic Dependencies and Remove Instability Issues



Place regulators only at few strategic places: **Low-Cost Acyclic Network (LCAN)**

Multi-path Topologies: **Our Contributions**

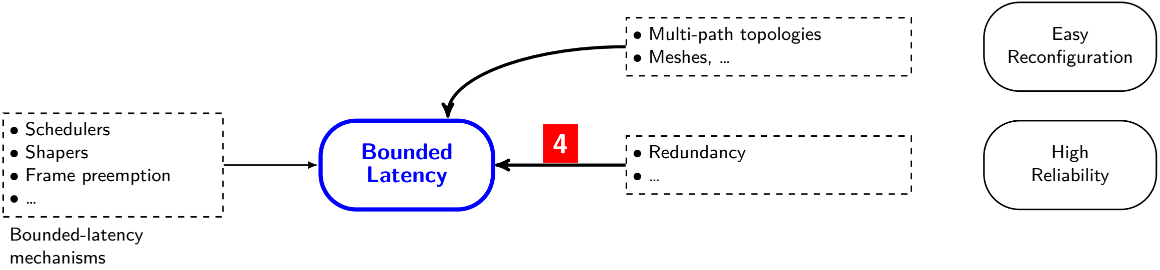
Contribution	Multipath topologies
End-to-end latency bounds	**FP-TFA**
Traffic regulators (PFRs and IRs)	LCAN

Ludovic Thomas, Jean-Yves Le Boudec, and Ahlem Mifdaoui [Dec. 2019]. "On Cyclic Dependencies and Regulators in Time-Sensitive Networks". In: *2019 IEEE Real-Time Systems Symposium (RTSS)*. DOI: 10.1109/RTSS46320.2019.00035

FP-TFA: Fixed-point total flow analysis
LCAN: Low-cost acyclic network

PFR: Per-flow regulator
IR: Interleaved regulator (=TSN ATS)

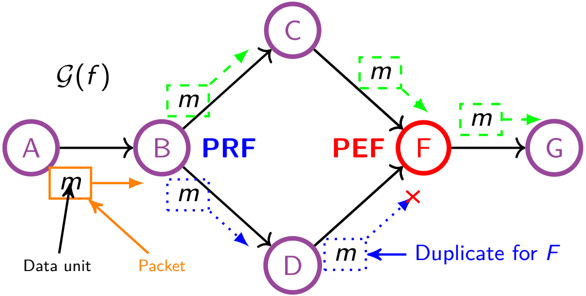
Redundancy Mechanisms



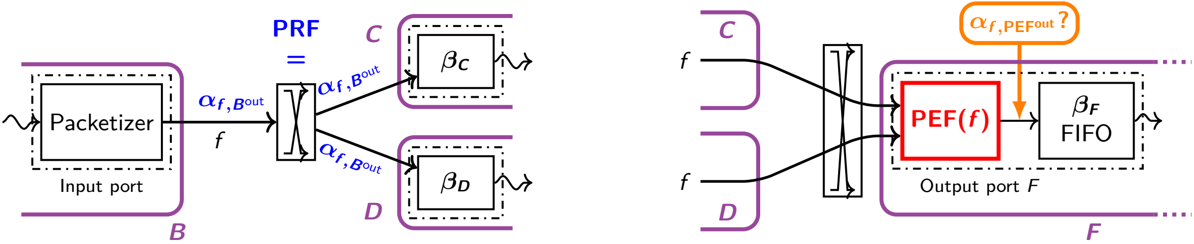
In TSN: Frame replication and elimination for redundancy [IEEE 802.1CB] (FRER)
In DetNet: Packet replication and elimination functions [RFC 8655] (**PREF**)

– [IEEE 802.1CB] "IEEE Standard for Local and Metropolitan Area Networks–Frame Replication and Elimination for Reliability" [Oct. 2017]. In: *IEEE Std 802.1CB-2017*. DOI: 10.1109/IEEESTD.2017.8091139
– [RFC 8655] Norman Finn, Pascal Thubert, Balázs Varga, and János Farkas [2019]. "Deterministic Networking Architecture". In: RFC 8655. DOI: 10.17487/RFC8655

Redundancy Relies on **Packet Replication (PRF)** and **Packet Elimination (PEF)** Functions

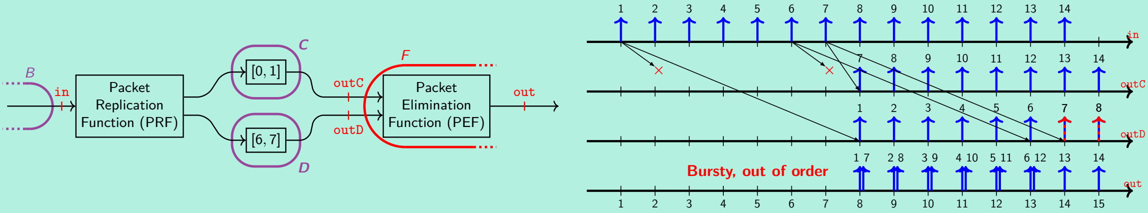


PRF Packet Replication Function
PEF Packet Elimination Function



What is the **Traffic at the Output** of the PEF ? (Packet Elimination Function)

A Possible Trajectory on a Toy Example

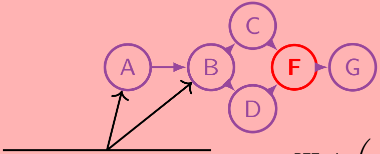


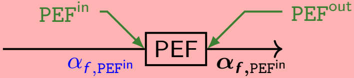
- Output of PEF bursty, mis-ordered ⇒ Can we bound the burstiness and mis-ordering at the PEF's output?
- Output bursty → leads to high delay in downstream ⇒ Place a traffic regulator after the PEF ?

An **Arrival Curve** at The Output of The PEF (Packet Elimination Function)

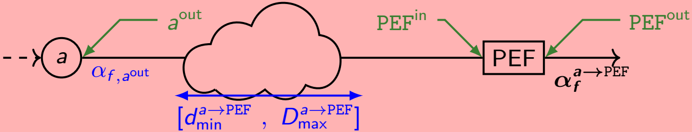
Theorem: PEF Output Arrival Curve

- $\alpha_{f,PEF^{in}}$ is an arrival curve at $\mathrm{PEF}^{\mathrm{out}}$





- $\forall a$, diamond ancestor, $\alpha_f^{a\rightarrow\mathrm{PEF}} \triangleq \left(\alpha_{f,a^{\mathrm{out}}} \oslash \delta_{\left(D_{\max}^{a\rightarrow\mathrm{PEF}} - d_{\min}^{a\rightarrow\mathrm{PEF}}\right)}\right)$ is an arrival curve at $\mathrm{PEF}^{\mathrm{out}}$



⇒ **Combine:** The min-plus convolution of all above arrival curves is an arrival curve at $\mathrm{PEF}^{\mathrm{out}}$.

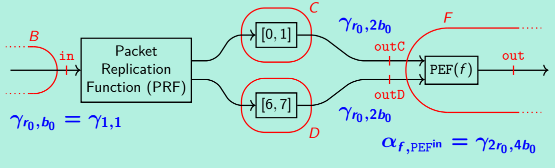
Applying our Result to the Toy Example Provides a **Tight Output Arrival Curve**

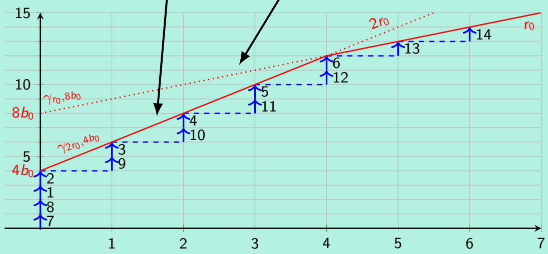
- $\alpha_{f,\mathrm{PEF}^{\mathrm{in}}} = \gamma_{2r_0,4b_0}$
- B is diamond ancestor

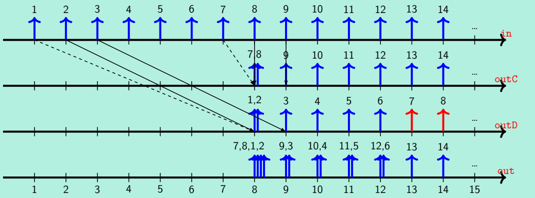
$$\alpha_f^{B\rightarrow\mathrm{PEF}} = \left(\alpha_{f,a^{\mathrm{out}}} \oslash \delta_{\left(D_{\max}^{a\rightarrow\mathrm{PEF}} - d_{\min}^{a\rightarrow\mathrm{PEF}}\right)}\right)$$

$$= \gamma_{r_0,b_0} \oslash \delta_7 = \gamma_{r_0,8b_0}$$

Toy example:







Question 1

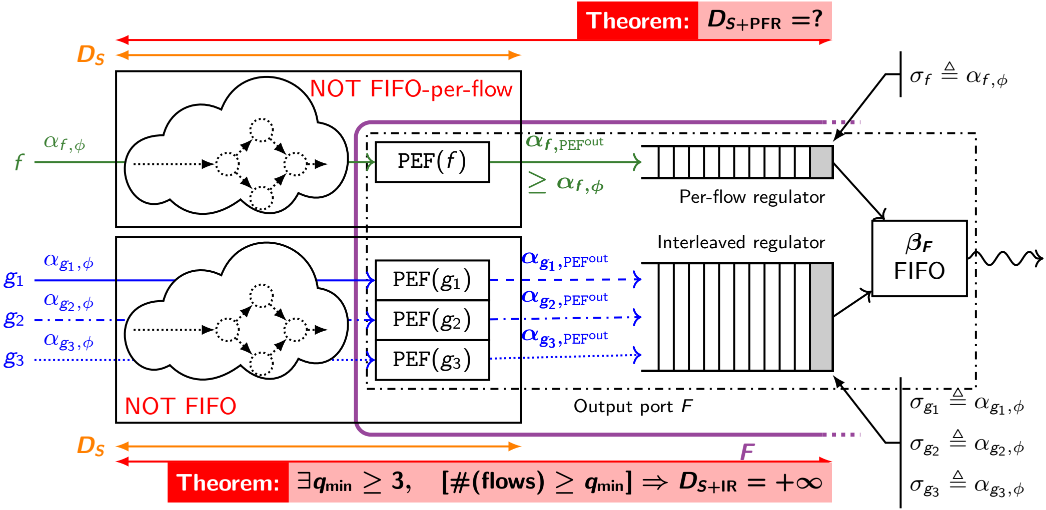
Output of PEF bursty, mis-ordered $\Rightarrow$ Can we bound the burstiness and mis-ordering at the PEF's output?

- Yes! Using novel network-calculus results.

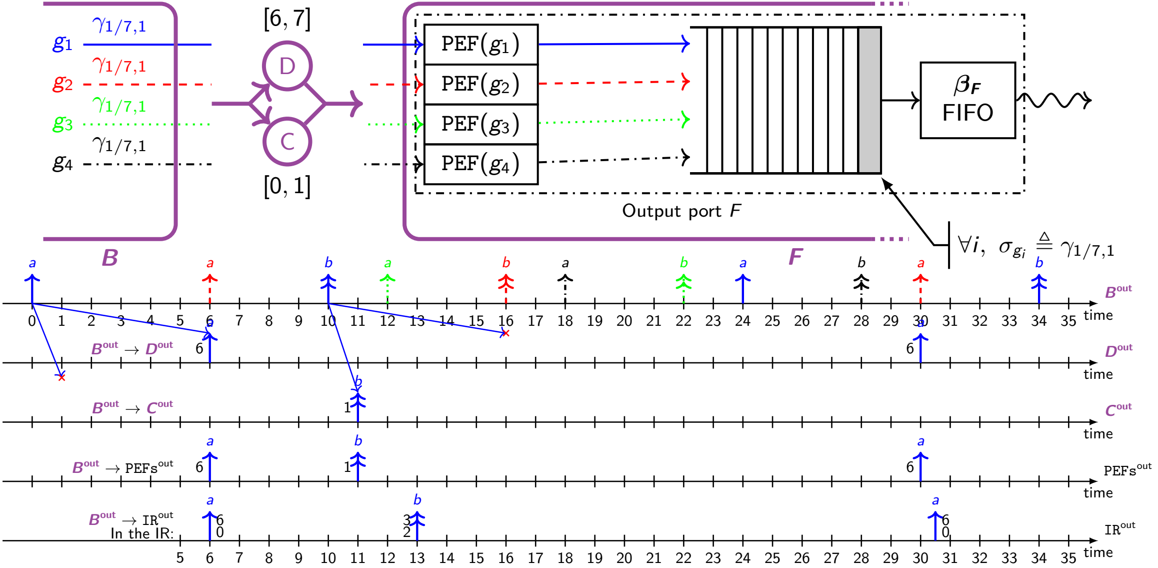
Question 2

Output bursty $\rightarrow$ leads to high delay in downstream $\Rightarrow$ Place a traffic regulator after the PEF ?

Combination of Traffic Regulators with Redundancy Functions: **FIFO assumption is lost**!



Interleaved Regulator (IR) Unstable after PEF: Intuition of the Proof



Redundancy Mechanisms: **Our Contributions**

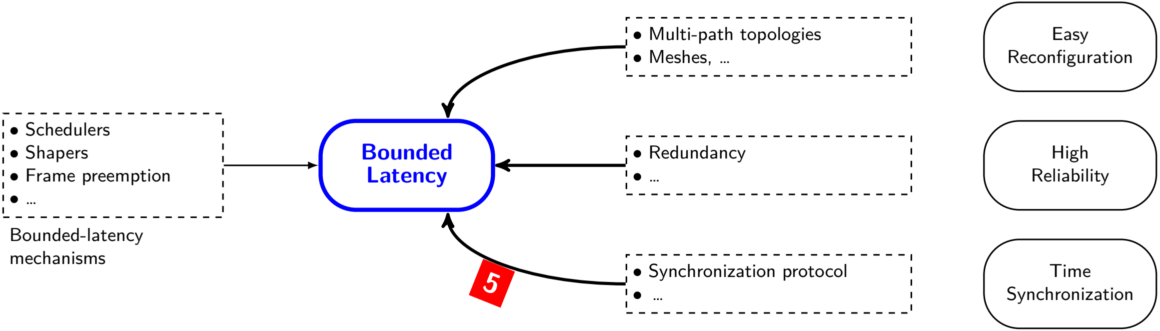
Contribution	Multipath topologies	Redundancy mechanisms
Network-calculus toolboxes		**Network-calculus model** for redundancy mechanisms
End-to-end latency bounds	**FP-TFA**	
Traffic regulators (PFRs and IRs)	LCAN	**IR Instability Result** Bounded penalty with PFR. Solution: POF (Packet Ordering Function)

Ludovic Thomas, Ahlem Mifdaoui, and Jean-Yves Le Boudec [2022]. “Worst-Case Delay Bounds in Time-Sensitive Networks With Packet Replication and Elimination”. In: *IEEE/ACM Transactions on Networking*. DOI: 10.1109/TNET.2022.3180763

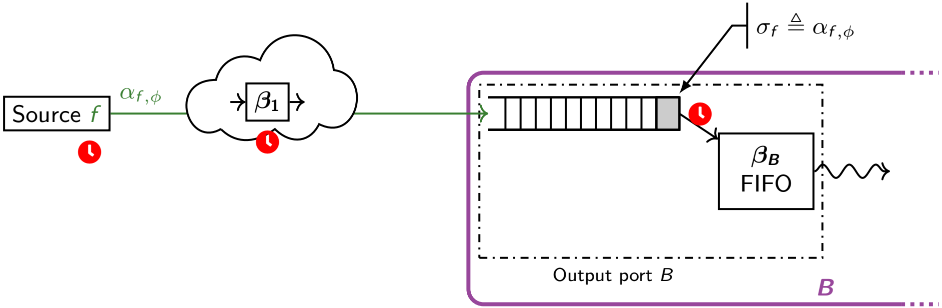
IR: Interleaved regulator (=TSN ATS)

PFR: Per-flow regulator

Time Synchronization and Clock Non-Idealities



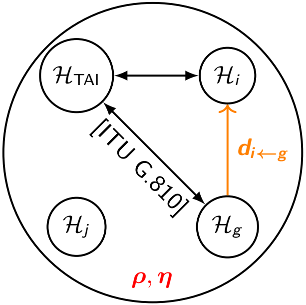
Motivation: Systems rely on their **own Internal Clock**



Discussions raised for TSN *Asynchronous Traffic Shaping* [IEEE 802.1Qcr]

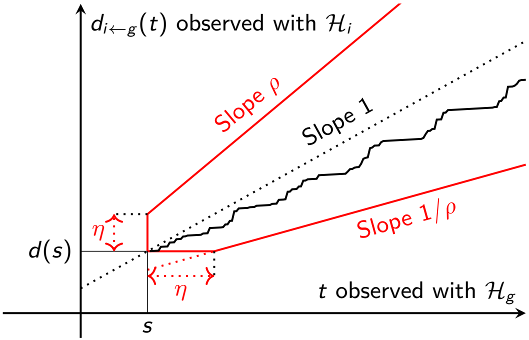
– [IEEE 802.1Qcr] "IEEE Standard for Local and Metropolitan Area Networks–Bridges and Bridged Networks - Amendment 34" [Nov. 2020]. "IEEE Standard for Local and Metropolitan Area Networks–Bridges and Bridged Networks - Amendment 34:Asynchronous Traffic Shaping". In: *IEEE Std 802.1Qcr-2020 (Amendment to IEEE Std 802.1Q-2018 as amended by IEEE Std 802.1Qcp-2018, IEEE Std 802.1Qcc-2018, IEEE Std 802.1Qcy-2019, and IEEE Std 802.1Qcx-2020)*. DOI: 10.1109/IEEESTD.2020.9253013

Model for Non-Synchronized Clocks



Non-synchronized model (ρ, η): $\forall i, g$,

$$\forall t, s \quad \frac{1}{\rho}(t - s - \eta) \leq d_{i\leftarrow g}(t) - d_{i\leftarrow g}(s) \leq (t - s)\rho + \eta$$



Parameters

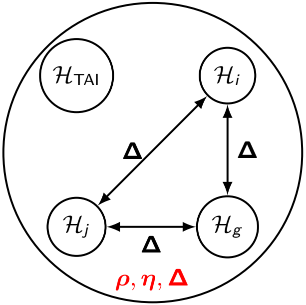
ρ Clock-stability bound
η Time-jitter bound

In TSN [IEEE 802.1AS]

$\rho = 1 + 200\text{ppm}$
$\eta = 4\text{ns}$

– [ITU G.810] ITU [1996]. "Definitions and Terminology for Synchronization Networks". In: *ITU G.810*
$\mathcal{H}_{\text{TAI}}$: international atomic time ("true time")

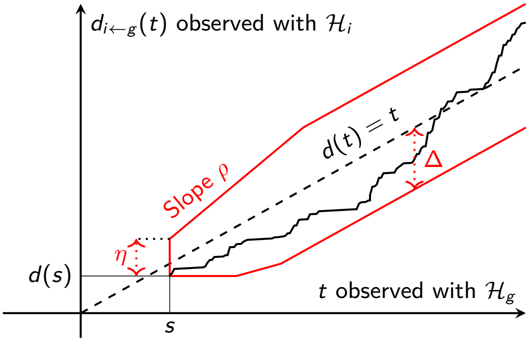
Model for Synchronized Clocks



Synchronized model (ρ, η): $\forall i, g$,

$$\forall t, s \quad \frac{1}{\rho}(t - s - \eta) \leq d_{i \leftarrow g}(t) - d_{i \leftarrow g}(s) \leq (t - s)\rho + \eta$$

$$\forall t, \quad |d_{i \leftarrow g}(t) - t| \leq \Delta$$



Parameters

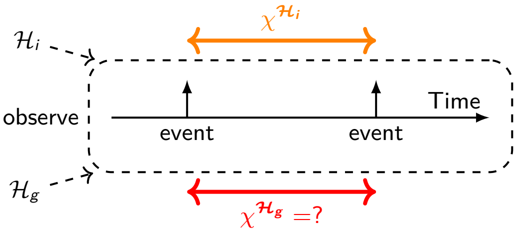
- ρ Clock-stability bound
- η Time-jitter bound
- Δ Synchronization precision

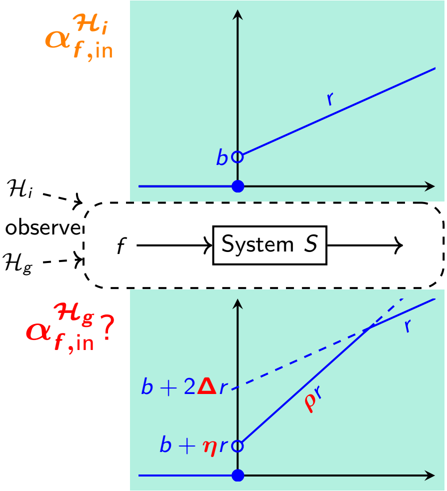
In TSN [IEEE 802.1AS]

- $\rho = 1 + 200\text{ppm}$
- $\eta = 4\text{ns}$
- $\Delta = 1\mu\text{s}$

– [IEEE 802.1AS] "IEEE Standard for Local and Metropolitan Area Networks–Timing and Synchronization for Time-Sensitive Applications" [June 2020]. In: *IEEE Std 802.1AS-2020 (Revision of IEEE Std 802.1AS-2011)*. DOI: 10.1109/IEEESTD.2020.9121845

A Toolbox of Results for **Changing the Observing Clocks**





Proposition [Changing clock for a duration]

$$\max\left(0, \frac{\chi^{\mathcal{H}_i}-\eta}{\rho}, \chi^{\mathcal{H}_i}-2\Delta\right) \leq \chi^{\mathcal{H}_g} \leq \min\left(\rho\chi^{\mathcal{H}_i}+\eta, \chi^{\mathcal{H}_i}+2\Delta\right)$$

$\Delta \triangleq +\infty$ if non-synchronized

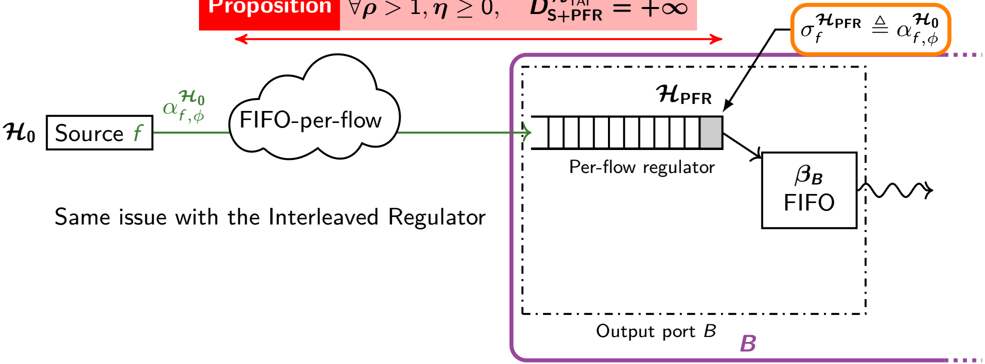
Proposition [Changing clock for an arrival curve]

$$\alpha_f^{\mathcal{H}_g} : t \mapsto \alpha_f^{\mathcal{H}_i}\left(\min\left[\rho t+\eta, t+2\Delta\right]\right)$$

Regulators and Non-Synchronized Clocks: **Unbounded Latencies**

Non-synchronized model: ρ, η

Proposition $\forall \rho > 1, \eta \geq 0, \quad D^{\mathcal{H}_{\text{TAI}}}_{\text{S+PFR}} = +\infty$



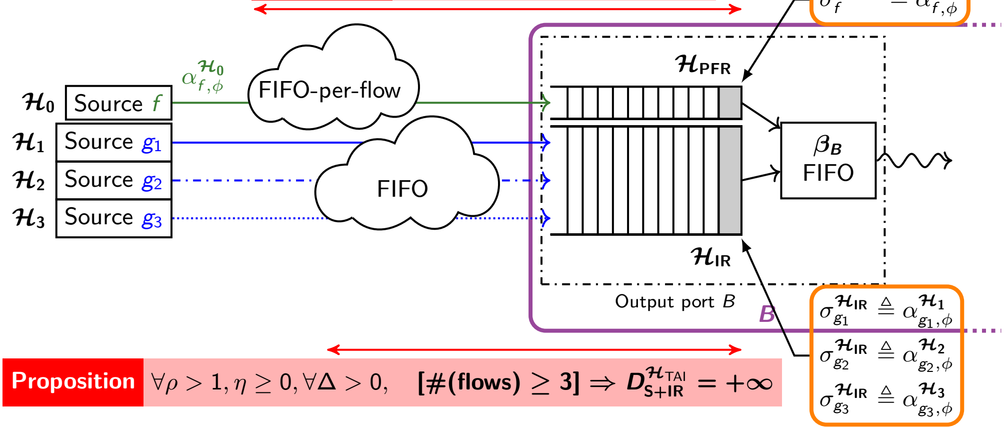
Same issue with the Interleaved Regulator

$\mathcal{H}_{\text{TAI}}$: international atomic time ("true time")

Combination of Traffic Regulators with a Time-Synchronization Protocol

Synchronized model: ρ, η, Δ

Proposition $\Delta \leq D^{\mathcal{H}_{\text{TAI}}}_{S+\text{PFR}} - D^{\mathcal{H}_{\text{TAI}}}_{S} \leq 4\Delta$



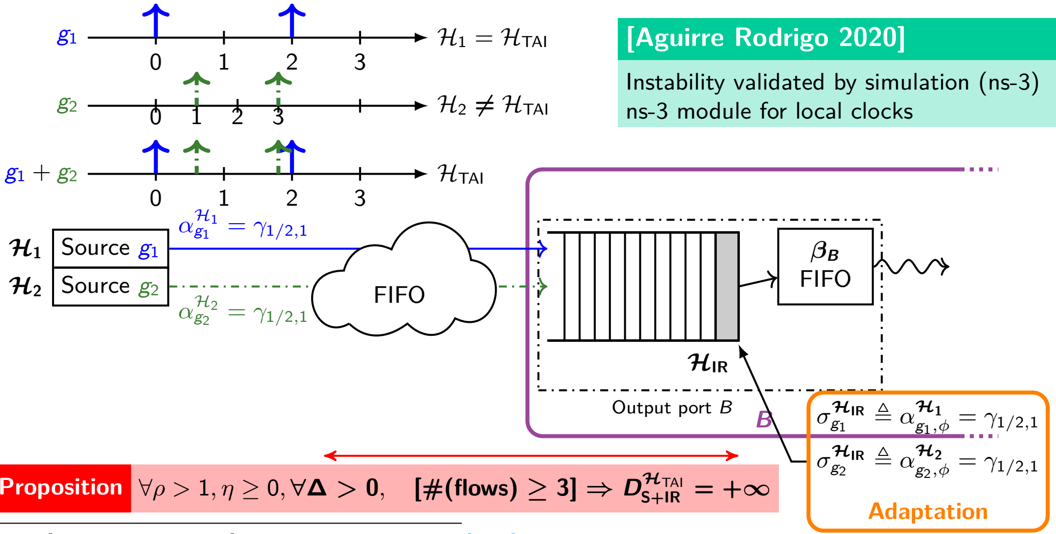
Proposition $\forall \rho > 1, \eta \geq 0, \forall \Delta > 0, \quad [\#(\text{flows}) \geq 3] \Rightarrow D^{\mathcal{H}_{\text{TAI}}}_{S+\text{IR}} = +\infty$

$\mathcal{H}_{\text{TAI}}$: international atomic time (“true time”)

Instability of the Interleaved Regulator with non-ideal Clocks: Intuition of the proof

[Aguirre Rodrigo 2020]

Instability validated by simulation (ns-3)
ns-3 module for local clocks



Proposition $\forall \rho > 1, \eta \geq 0, \forall \boldsymbol{\Delta} > \mathbf{0}, \quad [\#(\textbf{flows}) \geq 3] \Rightarrow D_{\text{S+IR}}^{\mathcal{H}_{\text{TAI}}} = +\infty$

– [Aguirre Rodrigo 2020] Guillermo Aguirre Rodrigo [2020]. *Simulation of Instability in Time-Sensitive Networks with Regulators and Imperfect Clocks.* EPFL/LCA2

Time Synchronization: **Our Contributions**

Contribution	Multipath topologies	Redundancy mechanisms	Time Synchronization
Network-calculus toolboxes		**Network-calculus model** for redundancy mechanisms	**Network-calculus model** for non-ideal clocks (sync/non-sync).
End-to-end latency bounds	**FP-TFA**		Two end-to-end strategies
Traffic regulators (PFRs and IRs)	LCAN	**IR Instability Results**	
		Bounded penalty with PFR. Solution: POF (Packet Ordering Function)	Bounded penalty with sync PFR. Solutions: ADAM and rate-and-burst cascade

Ludovic Thomas and Jean-Yves Le Boudec [June 9, 2020]. "On Time Synchronization Issues in Time-Sensitive Networks with Regulators and Nonideal Clocks". In: *Proceedings of the ACM on Measurement and Analysis of Computing Systems* 4.2. DOI: 10.1145/3392145

PFR: Per-flow regulator

IR: Interleaved regulator (=TSN ATS)

Experimental modular TFA, a **Tool for End-to-end Latency Bounds**

Contribution	Multipath topologies	Redundancy mechanisms	Time Synchronization
Network-calculus toolboxes		**Network-calculus model** for redundancy mechanisms	**Network-calculus model** for non-ideal clocks (sync/non-sync).
End-to-end latency bounds	**FP-TFA**		Two end-to-end strategies
Traffic regulators (PFRs and IRs)	LCAN	**IR Instability Results**	
		Bounded penalty with PFR. Solution: POF (Packet Ordering Function)	Bounded penalty with sync PFR. Solutions: ADAM and rate-and-burst cascade
Tools	experimental modular TFA (xTFA)		

PFR: Per-flow regulator

IR: Interleaved regulator (=TSN ATS)

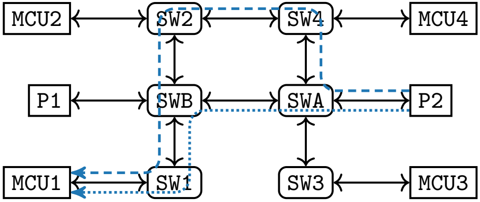
Application to an **Industrial Use-Case**

Contribution	Multipath topologies	Redundancy mechanisms	Time Synchronization
Network-calculus toolboxes		**Network-calculus model** for redundancy mechanisms	**Network-calculus model** for non-ideal clocks (sync/non-sync).
End-to-end latency bounds	**FP-TFA**		Two end-to-end strategies
Traffic regulators (PFRs and IRs)	LCAN	**IR Instability Results**	
		Bounded penalty with PFR. Solution: POF (Packet Ordering Function)	Bounded penalty with sync PFR. Solutions: ADAM and rate-and-burst cascade
Tools	experimental modular TFA (xTFA)		
Application	Validation on an industrial use-case		

PFR: Per-flow regulator

IR: Interleaved regulator (=TSN ATS)

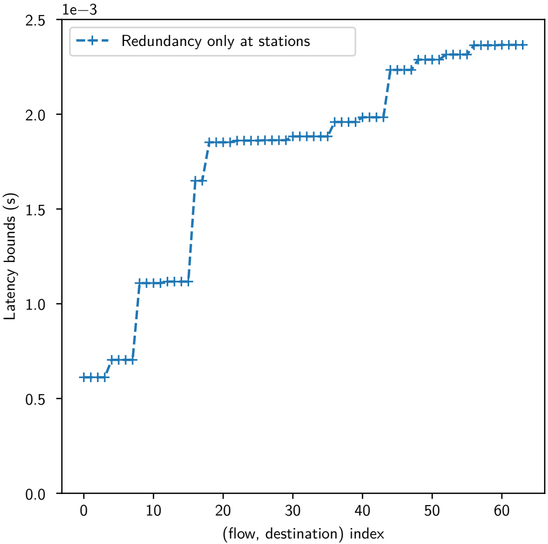
Use-Case: A **Multi-path Topology**



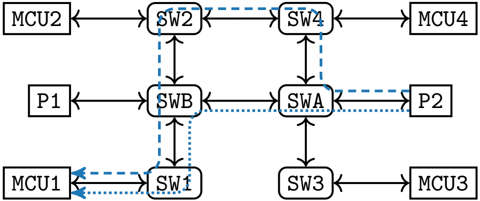
Based on the Volvo Core TSN Network

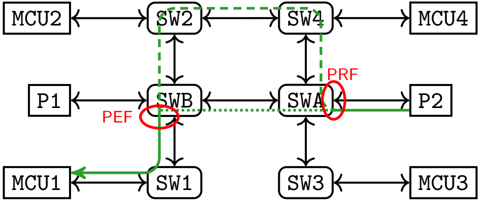
Nicolas Navet, Hoai Hoang Bengtsson, and Jörn Migge [Feb. 12, 2020]. "Early-Stage Bottleneck Identification and Removal in TSN Networks".

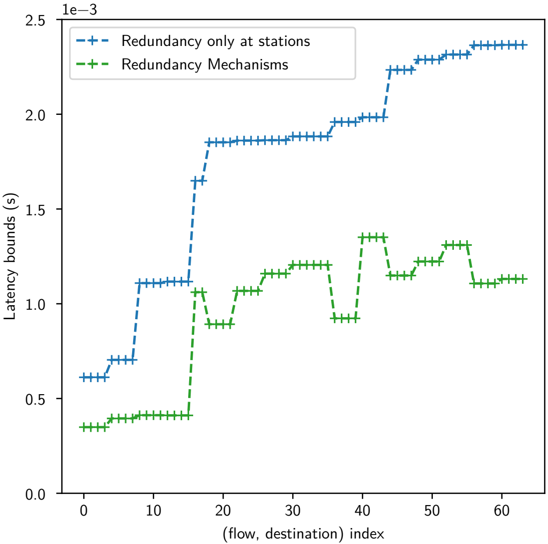
Profile	Payload size	Period at source
S	64B	81μs
M1	92B	324μs
M2	121B	567μs
B	150B	810μs



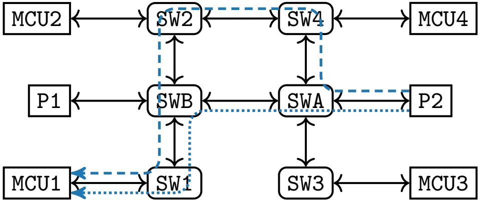
Use-Case: A **Multi-path Topology** with **Redundancy Mechanisms**



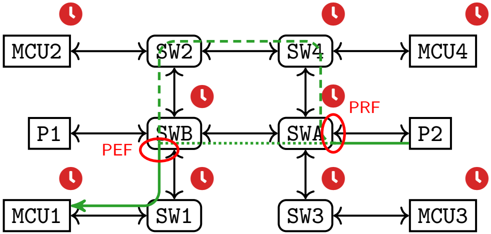


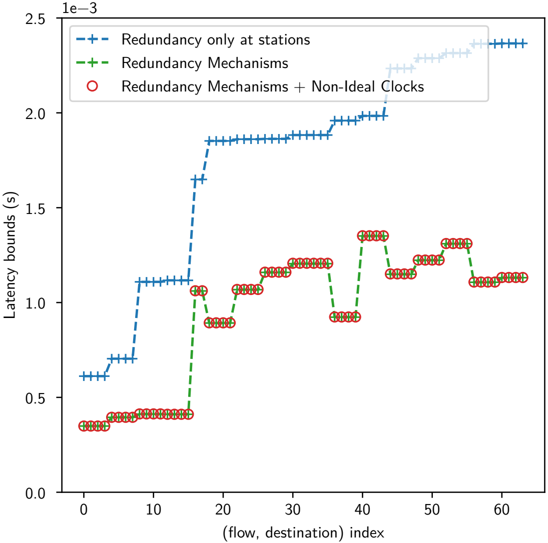


Use-Case: **Multi-path Topology** with **Redundancy Mechanisms** and **Time-Synchronization**



Tightly-synchronized $\Delta = 1\mu s$

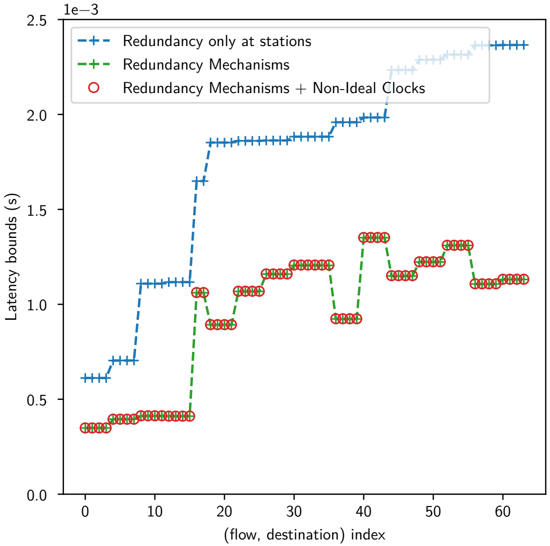




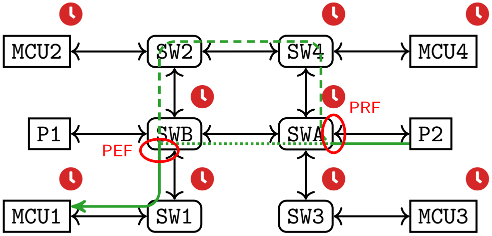
Use-Case: **Multi-path Topology** with **Redundancy Mechanisms** and **Time-Synchronization**

Take-away

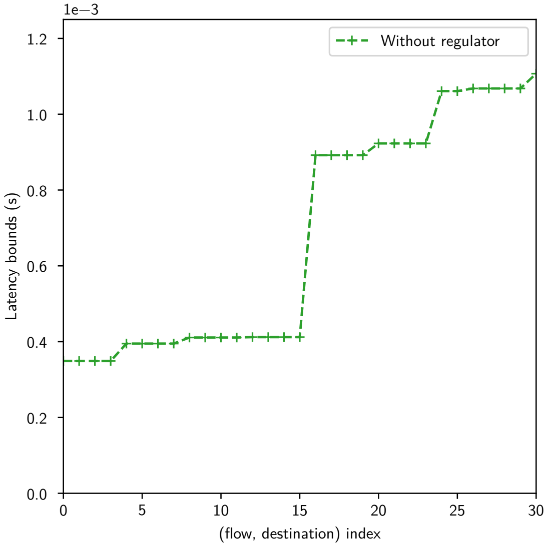
- Our model provides **better latency bounds** than those that assume redundancy only at end-systems.
- Clock non-idealities can be neglected in **tightly synchronized** networks that contain **no regulator**.



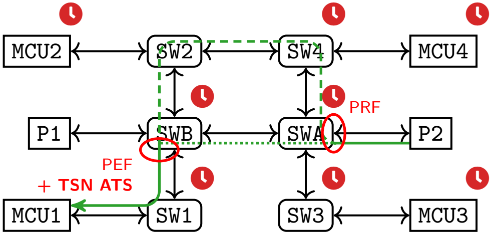
Use-Case: The Effect of **TSN ATS** (Interleaved Regulator)



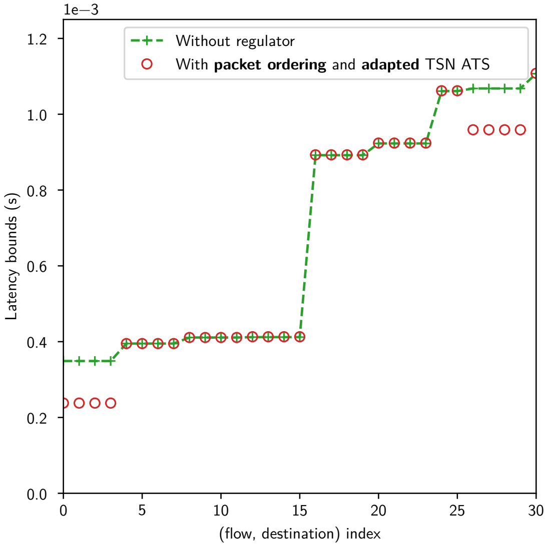
$\Delta =$



Use-Case: The Effect of **TSN ATS** (Interleaved Regulator)



$\Delta =$



Take-away

- Redundancy and clock non-idealities **cannot be neglected** when configuring IR / TSN ATS.
- If properly configured, TSN ATS **reduce latency bounds** when combined with redundancy mechanisms.

Summary of **our contributions**

Contribution	Multipath topologies	Redundancy mechanisms	Time-Synchronization
Network-calculus toolboxes		**Network-calculus model** for redundancy mechanisms	**Nework-calculus model** for non-ideal clocks (sync/non-sync).
End-to-end latency bounds	**FP-TFA**		Two end-to-end strategies
Traffic regulators (PFRs and IRs)	LCAN	**IR Instability Results**	
		Bounded penalty with PFR. Solution: Reordering	Bounded penalty with sync PFR. Solutions: ADAM and rate-and-burst cascade
Tools	**experimental modular TFA (xTFA)**		
			ns-3 module
	Validation on an industrial use-case		

FP-TFA: Fixed-point total flow analysis
LCAN: Low-cost acyclic network

PFR: Per-flow regulator
IR: Interleaved regulator (=TSN ATS)

Perspectives

Implement the model of redundancy mechanisms and non-ideal clocks in other compositional approaches

- Non-ideal clocks:
  - Service-curve-oriented approaches (SFA, PMOO) can benefit from the service-curve result.
  - Linear-constraints-oriented approaches can write the time models as linear constraints.
- Redundancy mechanisms: Results for service curves are missing!

The Quest for a Service Curve for TSN ATS

Does TSN ATS have a network calculus service-curve model?
$\Rightarrow$ Probably not (instability is too easy to achieve)

SFA: Separated Flow Analysis
TSN ATS: TSN Asynchronous Traffic Shaping
PMOO: Pay Multiplexing Only Once
IR: Interleaved Regulator

List of Publications

- Ludovic Thomas, Jean-Yves Le Boudec, and Ahlem Mifdaoui [Dec. 2019]. "On Cyclic Dependencies and Regulators in Time-Sensitive Networks". In: *2019 IEEE Real-Time Systems Symposium (RTSS)*. DOI: 10.1109/RTSS46320.2019.00035
- Ludovic Thomas and Jean-Yves Le Boudec [June 9, 2020]. "On Time Synchronization Issues in Time-Sensitive Networks with Regulators and Nonideal Clocks". In: *Proceedings of the ACM on Measurement and Analysis of Computing Systems* 4.2. DOI: 10.1145/3392145
- Ludovic Thomas, Ahlem Mifdaoui, and Jean-Yves Le Boudec [2022]. "Worst-Case Delay Bounds in Time-Sensitive Networks With Packet Replication and Elimination". In: *IEEE/ACM Transactions on Networking*. DOI: 10.1109/TNET.2022.3180763

Bibliography I

[Aguirre Rodrigo 2020] Aguirre Rodrigo, Guillermo (2020). *Simulation of Instability in Time-Sensitive Networks with Regulators and Imperfect Clocks*. EPFL/LCA2. 80 pp. URL: https://infoscience.epfl.ch/record/294616.

[Andrews 2009] Andrews, Matthew (July 2009). "Instability of FIFO in the Permanent Sessions Model at Arbitrarily Small Network Loads". In: *ACM Trans. Algorithms* 5.3, 33:1–33:29. ISSN: 1549-6325. DOI: 10.1145/1541885.1541894. URL: http://doi.acm.org/10.1145/1541885.1541894 (visited on 04/10/2019).

[Bouillard, Boyer, Le Corronc 2018] Bouillard, Anne, Marc Boyer, and Euriell Le Corronc (2018). *Deterministic Network Calculus: From Theory to Practical Implementation*. Networks and Telecommunications. Wiley. ISBN: 978-1-84821-852-9. URL: http://doi.org/10.1002/9781119440284.

[Finn, *et al.* 2019] Finn, Norman et al. (2019). "Deterministic Networking Architecture". In: RFC 8655. ISSN: 2070-1721. DOI: 10.17487/RFC8655. URL: https://www.rfc-editor.org/info/rfc8655 (visited on 06/07/2021).

[Le Boudec, Thiran 2001] Le Boudec, Jean-Yves and Patrick Thiran (2001). *Network Calculus: A Theory of Deterministic Queuing Systems for the Internet*. Lecture Notes in Computer Science, Lect.Notes Computer. Tutorial. Berlin Heidelberg: Springer-Verlag. ISBN: 978-3-540-42184-9. URL: https://www.springer.com/us/book/9783540421849 (visited on 02/04/2019).

Bibliography II

[Mifdaoui, Leydier 2017] Mifdaoui, Ahlem and Thierry Leydier (Dec. 2017). "Beyond the Accuracy-Complexity Tradeoffs of Compositional Analyses Using Network Calculus for Complex Networks". In: *10th International Workshop on Compositional Theory and Technology for Real-Time Embedded Systems (Co-Located with RTSS 2017)*. Paris, France, pp. 1–8. URL: https://hal.archives-ouvertes.fr/hal-01690096 (visited on 04/12/2019).

[Mohammadpour, Stai, Le Boudec 2019] Mohammadpour, E., E. Stai, and J.-Y. Le Boudec (2019). "Improved Delay Bound for a Service Curve Element with Known Transmission Rate". In: *IEEE Networking Letters*, pp. 1–1. DOI: 10.1109/LNET.2019.2927143. URL: http://doi.org/10.1109/LNET.2019.2927143.

[RFC 8655] Finn, Norman et al. (2019). "Deterministic Networking Architecture". In: RFC 8655. ISSN: 2070-1721. DOI: 10.17487/RFC8655. URL: https://www.rfc-editor.org/info/rfc8655 (visited on 06/07/2021).

[IEEE 802.1Qcr] "IEEE Standard for Local and Metropolitan Area Networks–Bridges and Bridged Networks - Amendment 34" (Nov. 2020). "IEEE Standard for Local and Metropolitan Area Networks–Bridges and Bridged Networks - Amendment 34:Asynchronous Traffic Shaping". In: *IEEE Std 802.1Qcr-2020 (Amendment to IEEE Std 802.1Q-2018 as amended by IEEE Std 802.1Qcp-2018, IEEE Std 802.1Qcc-2018, IEEE Std 802.1Qcy-2019, and IEEE Std 802.1Qcx-2020)*, pp. 1–151. DOI: 10.1109/IEEESTD.2020.9253013.

Bibliography III

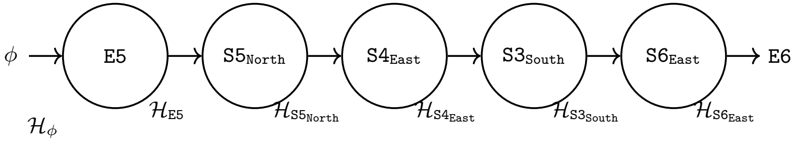
[IEEE 802.1CB] "IEEE Standard for Local and Metropolitan Area Networks–Frame Replication and Elimination for Reliability" (Oct. 2017). In: *IEEE Std 802.1CB-2017*, pp. 1–102. DOI: 10.1109/IEEESTD.2017.8091139.

[IEEE 802.1AS] "IEEE Standard for Local and Metropolitan Area Networks–Timing and Synchronization for Time-Sensitive Applications" (June 2020). In: *IEEE Std 802.1AS-2020 (Revision of IEEE Std 802.1AS-2011)*, pp. 1–421. DOI: 10.1109/IEEESTD.2020.9121845.

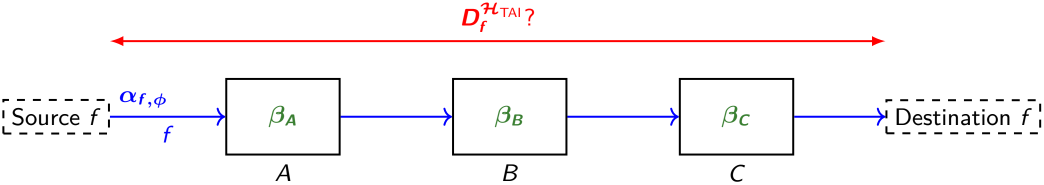
[ITU G.810] ITU (1996). "Definitions and Terminology for Synchronization Networks". In: *ITU G.810*. URL: https://www.itu.int/rec/T-REC-G.810-199608-I/en (visited on 10/14/2019).

[RFC 793] *Transmission Control Protocol* (Sept. 1981). RFC 793. DOI: 10.17487/RFC0793. URL: https://rfc-editor.org/rfc/rfc793.txt.

Computing End-to-end Latency Bounds in the True Time with TFA



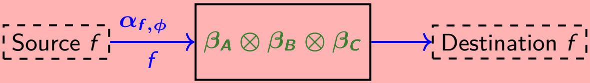
End-To-End Latency Bounds



If f is alone:

Theorem (Concatenation)

$\Leftrightarrow$



Also known as *Pay Burst Only Once* (PBOO)

$\otimes$: min-plus convolution. $(\mathfrak{f} \otimes \mathfrak{g}) : t \mapsto \inf_{0 \leq s \leq t}\{\mathfrak{f}(t-s) + \mathfrak{g}(s)\}$

The Always In TAI Strategy

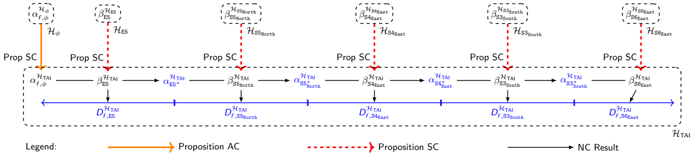
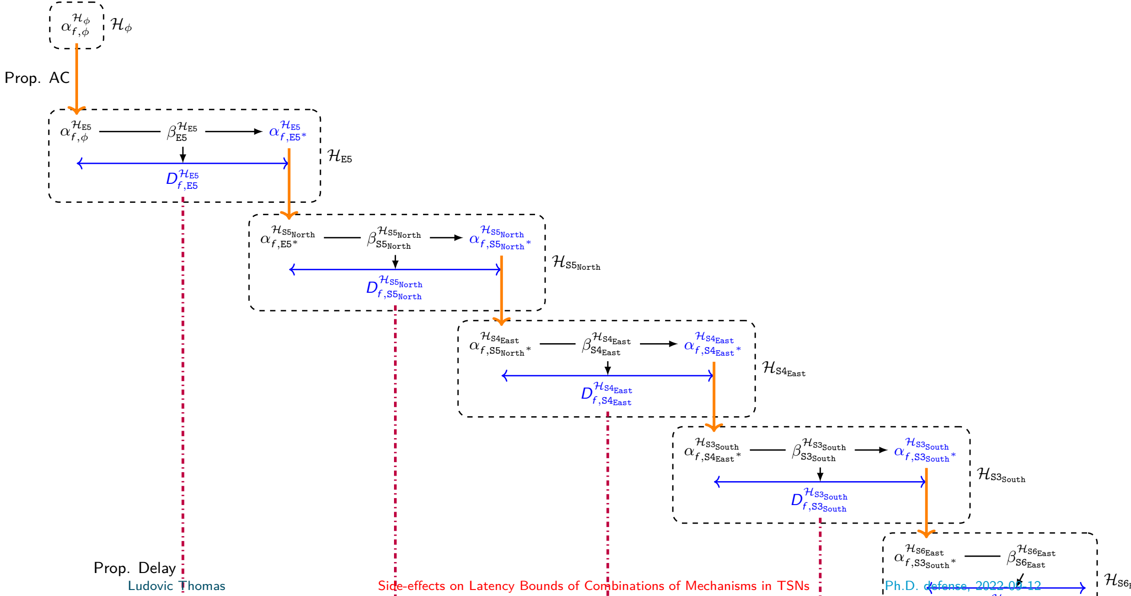


Figure: Illustration of the strategy "always in $\mathcal{H}_{\mathsf{TAI}}$" for the example

The Always In Local Time



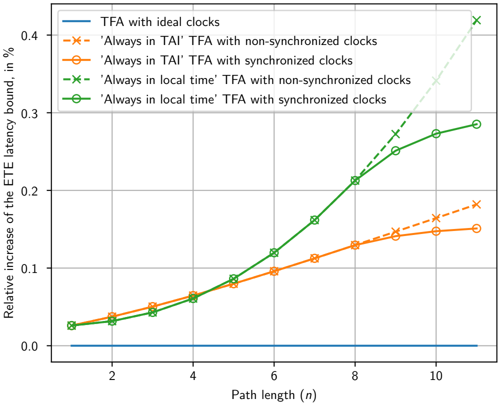
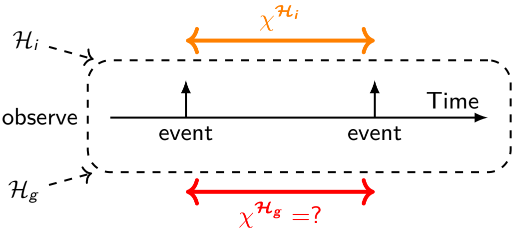


Figure: End-to-end latency bounds as a function of the path length, obtained either with the "always in TAI" strategy or with the "always in local time strategy", in synchronized and non-synchronized networks.

A Toolbox of Results for **Changing the Observing Clocks**



Proposition [Changing clock for a duration]

$$\max\left(0, \frac{\chi^{\mathcal{H}_i} - \eta}{\rho}, \chi^{\mathcal{H}_i} - 2\Delta\right) \leq \chi^{\mathcal{H}_g} \leq \min\left(\rho\chi^{\mathcal{H}_i} + \eta, \chi^{\mathcal{H}_i} + 2\Delta\right)$$

$\Delta \triangleq +\infty$ if non-synchronized

Proposition [Changing clock for an arrival curve]

$$\alpha_f^{\mathcal{H}_g} : t \mapsto \alpha_f^{\mathcal{H}_i}\left(\min\left[\rho t + \eta, t + 2\Delta\right]\right)$$